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Use of Lasers to Control Selective Chemical Reactions

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In recent years much progress has been made in widening the range of laser wavelengths and in developing the tuning, control, and stabilization of the laser radiation frequency. This has made it possible to begin a systematic investigation of the control of selective chemical reactions with laser radiation. This problem is of fundamental importance for the use of coherent light in chemistry, particularly photochemistry and nuclear chemistry, and possibly in biology, medicine, and other fields. The general idea, which appeared 50 years ago, is that it is possible to use the differences in the absorption spectra of substances—the existence of which is evidence for their selective interaction with light—not only to analyze the composition and structure of the substances, but to selectively influence them to change their composition and properties.

Let us consider a mixture of molecules A and B, which are very close in their chemical properties, and let one of them, say A, be made to react with a certain compound R. Chemists have at their disposal quite a number of methods of catalyzing chemical reactions. However, in many cases their efficiency is very low. One can introduce the selectivity coefficient as the ratio of the number of reacted A molecules to the number of B molecules entering reaction, their initial concentrations being equal:

$$S = \frac{K_{AR}}{K_{BR}} - 1 \tag{1}$$

When there is no selectivity $K_{AR} = K_{BR}$, that is, the selectivity coefficient $S = 0$. For example, for molecules A and B that are different only in their isotopic composition S is much less than unity (0.01 to 0.03).

It appears quite natural to make use of the difference in the absorption spectra of molecules A and B, when it exists, for the selective excitation of molecules of a definite type (*1*). The reaction rate of excited A molecules can be essentially different from that of nonexcited ones, and in such cases we can achieve considerable selectivity. If the reaction rates do not depend on the excitation of an atom or a molecule, then one can use a change in other properties with excitation, in particular a change in the dissociation energy of a molecule.

The first attempts to realize a selective photocatalysis of chemical reactions, the most difficult case relating to isotopic molecules, date from the early thirties and even the twenties. In one of the first (*2*), the authors attempted to carry out the reaction of chlorine-37 with hydrogen under excitation with white light that was filtered by chlorine mainly consisting of chlorine-35. In 1930 (*3*) the selective reaction of "ortho" iodine molecules with hexane was achieved by exciting the "ortho" but not the "para" molecules by the 5461-angstrom line of the mercury spark. The first successful photochemical isotope separation was reported in (*4*); the 2816.179-Å line of the aluminum spark excited phosgene molecules, $CO^{35}Cl^{35}Cl$, which decomposed in subsequent collisions. It was suggested (*5*) that definite Hg isotopes could be excited in vapors by using the 2537-Å resonance line of the Hg lamp with a definite Hg isotope, and that chemical reactions with excited Hg atoms could be observed; these experiments were successfully performed (*6*). In subsequent work the photochemical separation of isotopes of chlorine (*7*), mercury (*8*), and carbon and oxygen (*9*) was observed by using coincidences of the intense lines of spontaneous radiation with absorption lines.

Selectivity Conditions for Photochemical Reactions

For the selective action of radiation on a substance, three conditions must be fulfilled. There must be

1) High monochromaticity of the exciting radiation with a necessary power level at a given frequency.

2) Selectivity of the elementary process of interaction between the radiation and the substance (existence of narrow absorption lines).

3) Conservation of the selectivity obtained in subsequent physical and chemical processes.

Achievement of the first condition with the usual light sources was rather difficult. Only at rare definite frequencies could one obtain narrow lines of the spontaneous radiation with sufficient intensity. The first condition can be carried out in the visible, ultraviolet, and infrared regions with lasers. In fact, not only is the great spectral brightness of the laser radiation sufficient for selective photocatalysis, but the frequency tuning of the laser radiation makes it possible to excite any level of the atom or molecule chosen.

The second condition can be fulfilled with a substance in the gas phase when there is interaction with the electronic and vibrational transitions between the states of the discrete energy spectrum. Under particular conditions it can also be fulfilled for the substance in a condensed state, and here there are great

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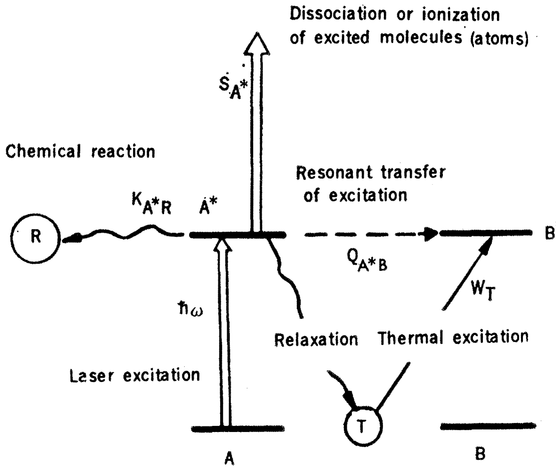


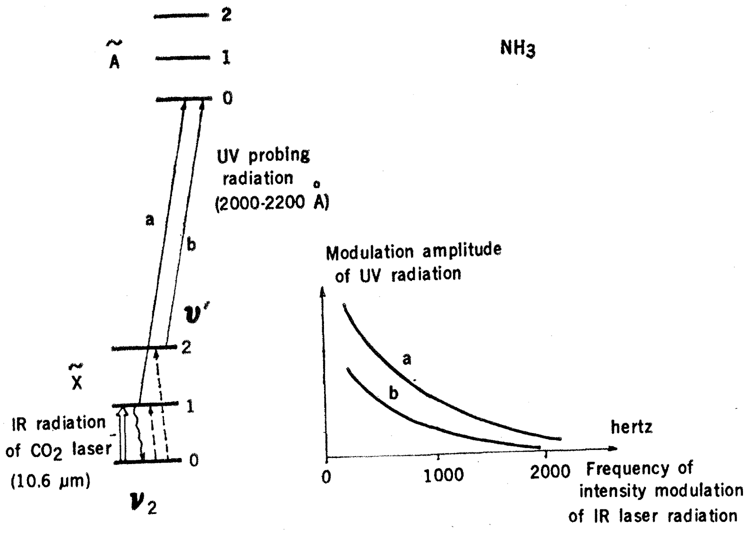


Fig. 1 (left). Classification of processes causing the loss and conservation of selectivity. Fig. 2 (right). Method of investigating the mechanism of excitation of NH_3 vibrational levels by continuous CO_2 laser radiation. Transitions are denoted by *a* and *b*; UV, ultraviolet; IR, infrared.

possibilities for using selective photocatalysis in biology and medicine.

It is a much more complicated problem to satisfy the third condition, since the selectivity obtained as a result of the primary photochemical act (excitation) can easily be lost after many subsequent processes. In Fig. 1 the processes leading to both loss of selectivity and conservation of selectivity in the irradiated substance are represented in a simplified way. Suppose the laser radiation selectively excites an electronic or vibrational level of the A molecule in a mixture with B molecules. (Everything said below refers equally to a mixture of atoms.) The problem, as before, is to have selective bonding of A molecules. Loss of selectivity is caused by two processes:

1) Thermal nonselective excitation. The excited molecules can relax into the ground state before a chemical reaction takes place. For vibrational levels of molecules the relaxation is of a nonradiative character, and consequently leads to a heating of the gas mixture up to a certain temperature *T*. It results in a thermal population of vibrational levels of both types of molecules with the Boltzmann probability exp $(-E/kT)$, where *E* is the energy of a level and *k* is Boltzmann's constant. The thermal excitation is completely nonselective, and molecules of both types react with the same rate under irradiation.

2) Resonant transfer of excitation. This takes place when the excited A molecule, A*, collides with the nonexcited:

$$A^* + B \rightarrow A + B^*$$

The cross section for resonance transfer of excitation among molecules with close resonance levels has the gas kinetic value, and among atoms with close resonance levels it can be hundreds of times more. Therefore the transfer of excitation occurs at every collision, that is, with a rate exceeding that of a typical chemical reaction.

To carry out a selective chemical reaction with atoms or molecules of one type, A, there are two principal possibilities.

1) Fast chemical reaction. That is, the chemical reaction between the selectively excited particle A* and a special chemical compound R (the acceptor) goes with a rate K_{A^*R} which exceeds the rate of resonance transfer of excitation, Q_{A^*B}, and the rate of thermal excitation, W_T:

$$K_{A^*R} \gg Q_{A^*B}, W_T \qquad (2)$$

2) Dissociation or ionization of excited particles. It is possible to induce a transition of selectively excited A* particles into another state, in which the selectivity loss rate is considerably less. This can be done by the photoionization of selectively excited atoms or the photodissociation of selectively excited molecules. Again, this process should go with a rate S_{A^*}, exceeding the rate of resonance transfer of excitation and that of the thermal excitation:

$$S_{A^*} \gg Q_{A^*B}, W_T \qquad (3)$$

In contrast to the method of chemical bonding, this method is universal, since condition 3 can always be fulfilled by using the fast photoionization of atoms or photodissociation of molecules with an additional sufficiently intense laser radiation.

In this article these problems are considered together with experimental data obtained recently at the Institute of Spectroscopy of the U.S.S.R. Academy of Sciences.

Thermal Mechanism of Selectivity Loss

The role of the thermal mechanism of selectivity loss was investigated by irradiating ammonia molecules with a 10-micrometer carbon dioxide laser by the following method (*10*) (Fig. 2). We measured a population of vibrational levels of NH_3 by the intensity of the ultraviolet absorption lines corresponding to transitions from the vibrational levels of the ground electronic state of the molecule into the excited electronic state. Discrimination of the two simultaneous excitation mechanisms, laser and thermal, was achieved in the following way. The intensity of the CO_2 laser radiation was modulated at an audio frequency. If the population of levels is determined by the laser excitation, it should follow the intensity of the laser radiation when the modulation period is larger than the molecular lifetime in a vibrational level. In the case of the thermal excitation due to its inertia (the thermal relaxation time being approximately 1 millisecond), the modulation amplitude of the level population should fall under an increase of the modulation frequency up to 1 kilohertz. This is just what was observed in the experiment for several vibrational levels of NH_3. Chemical reactions of gas mixtures with NH_3 irradiated by a CO_2 laser are expected to be of a pure thermal character.

When the gas mixture is irradiated with a pulsed laser, thermal excitation also becomes essential for the level population. In Fig. 3 the dependence of the population of NH_3 vibrational levels on the action of the CO_2 laser is illustrated; this was measured by experiment (*11*). During the laser pulse and the time when the vibrational relaxation is small, the level population is determined by the laser excitation. During the relaxation of the excited molecules and the following heating of the gas the mechanism of thermal excitation begins, and it remains effective for a much longer period of time. So, the selective excitation lives for a rather short time (1 microsecond for NH_3 at a pressure of several dozens of torrs), and the nonselective thermal excitation occurs for about 1 millisecond. The proportions of selective and nonselective processes are distributed respectively.

Let us note that in the excitation of the electronic levels of atoms and molecules, where the energy is many times the average thermal energy kT, thermal nonselective excitation does not, in fact, influence the reaction rate.

Loss of Selectivity Due to Resonance Exchange by Excitation

Resonance exchange by excitation in collisions results in an irreversible loss of the excitation selectivity. It occurs with excited electronic states of atoms and molecules and excited vibrational states of molecules. For instance, the excitation exchange with bromine of mixed isotopic composition prevented separation of the isotopes ^{79}Br and ^{81}Br (*12*). The resonance transfer of vibrational excitation among NH_3 molecules differing in their isotopic composition was studied (*13*) (Fig. 4). The radiation of the CO_2 pulsed laser was in resonance with the rotational-vibrational transition $Q(5,3)\nu_2$ of the $^{14}NH_3$ molecules, but it was not absorbed by the $^{15}NH_3$ molecules, which were present in the gas mixture in nearly the same number. Because of the transfer of excitation between isotopic NH_3 molecules the population of the upper vibrational level should increase, and consequently the absorption coefficient of the $^{15}NH_3$ transitions should decrease; that is, the $^{15}NH_3$ bleaching pulse occurs. It was measured with the CO_2 continuous-wave laser, whose frequency was tuned to another rotational-vibrational transition $aR(0,0)\nu_2$ of $^{15}NH_3$, which is noncoincident with $^{14}NH_3$ transitions. So, two lasers were in resonance with various molecules, among which the excitation resonance transfer occurred. In the right-hand corner of Fig. 4 the $^{15}NH_3$ bleaching pulse is shown. The $^{15}NH_3$ transmission pulse arose without delay after the excitation pulse, from which the number of molecular collisions needed for excitation transfer can be evaluated: $Z(^{14}NH_3 \leftrightarrow {}^{15}NH_3) < 10$. However, when the gas mixture is diluted with helium the bleaching signal vanishes. This means that the buffer gas quenches vibrationally excited $^{14}NH_3$ molecules before they collide with $^{15}NH_3$, and in this way prevents the transfer of excitation from $^{14}NH_3$ to $^{15}NH_3$. This buffer gas method can facilitate the fulfillment of conditions 2 and 3 for realizing selective processes with molecules having a definite isotopic composition.

Excitation of High Vibrational Levels by Vibrational Exchange

Two vibrationally excited molecules can collide, with a de-excitation of one molecule and a transition of the other into the next vibrational level:

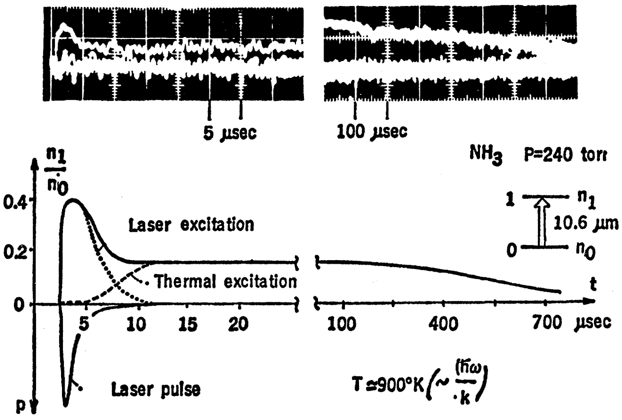
$$A(v' = 1) + A(v' = 1) \rightarrow A(v' = 0) + A(v' = 2)$$

where $v' = 0$, 1, 2 denote the vibrational levels. If the time of the vibrational-vibrational exchange, τ_{vv}, is less than that of the vibrational-translational relaxation, τ_{vt}:

$$\tau_{vv} \ll \tau_{vt}, \text{ that is } Z_{vv} \ll Z_{vt}$$

where Z_{vv} and Z_{vt} are the average number of collisions necessary for vibrational excitation exchange and vibrational-translational relaxation, respectively, then, in principle, one can excite high vibrational levels with energy E considerably in excess of an energy quantum $\hbar\omega$ and of kT. This will correspond to a nonequilibrium gas state with the "vibrational" temperature considerably exceeding the "translational" one.

Such a possibility is considered from the theoretical point of view in (*14*). What is the excitation selectivity in this mechanism? Let the vibrational heating by radiation be carried out with A molecules in a mixture with B molecules; it is necessary that the A molecules, and not the B molecules, be involved in the reaction (Fig. 5). If the frequencies of molecules A and B differ greatly from each other we can expect the vibrational heating of only A molecules, and a following chemical reaction only with them. In this case one can hope to carry out reactions with the activation energy E_a considerably exceeding a quantum of energy $\hbar\omega$.



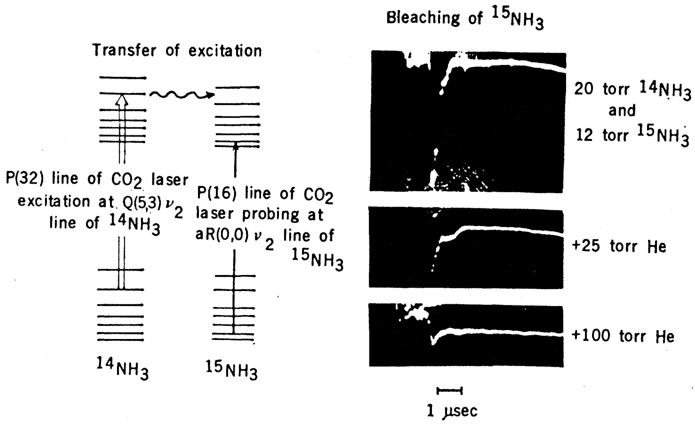


Fig. 3 (left). Population dependence of the first vibrational level of NH_3 on the CO_2 laser radiation pulse. The populations of the ground state and first vibrational level are n_0 and n_1, respectively. Fig. 4 (right). Method of investigating resonance transfer of vibrational excitation between molecules.

If the vibrational frequencies of the molecules are similar, as is the case for molecules differing only in their isotopic composition, then the resonance vibrational-vibrational exchange between A and B will result in the excitation of vibrational levels of both types and in loss of selectivity of the chemical reaction. This action of the laser radiation can be called selective-limited, as the selectivity in this case is achieved only when there is a considerable difference between the molecular vibrational frequencies, much more than is necessary for a difference in the absorption spectra.

The selective-limited reactions stimulated by laser radiation were reported by Basov *et al.* (*15*). This type of stimulation is of great interest, since with it one can obtain chemical reactions of large volume in a short period of time and produce some reaction products not available with other methods (*15, 16*). It is important that in this case it is really possible to carry out reactions with the activation energy greater than $\hbar\omega$. However, it is achieved at the cost of a loss of selectivity for isotopic molecules.

In exciting high vibrational levels by means of vibrational-vibrational exchange under laser pumping of the first vibrational state, there is the "narrow throat" effect which essentially limits the excitation rate. The monochromatic radiation excites only a small fraction, q, of the molecules in the rotational-vibrational sublevel. To increase the excitation rate it is necessary to increase the radiation intensity. However, if the excitation rate W_{exc} for the molecules in the lower sublevel becomes much higher than the rotational relaxation rate $1/\tau_{\text{rot}}$, then the lower sublevel quickly becomes depleted. The next excitation is possible only when it is filled through rotational relaxation (Fig. 6). As a result the rate of increase of the molecules' vibration energy E_{vib} under the resonance infrared radiation satisfies the relation (*17*):

$$\frac{dE_{\text{vib}}}{dt} < \frac{\hbar\omega}{2}\frac{q}{\tau_{\text{rot}}} \tag{4}$$

where $q \ll 1$ is the fraction of the molecules interacting with the radiation and τ_{rot} is the rotational relaxation time. To excite half of the molecules with a pulse of duration τ_{p}, it is necessary that $\tau_{\text{p}} > \tau_{\text{rot}}/q$. So, a typical time for vibrational excitation of the molecules is

$$\tau_{\text{exc}} = \tau_{\text{rot}}/q = \tau_{\text{coll}}\,(Z_{\text{rot}}/q)$$

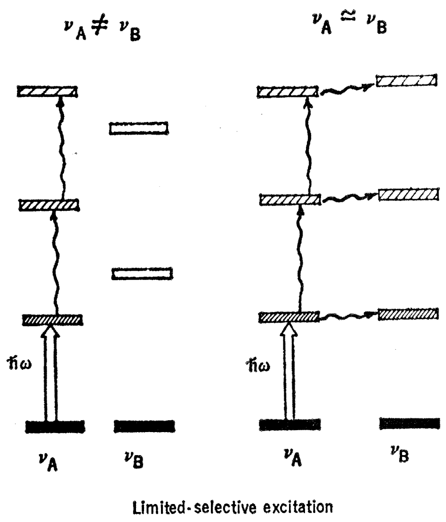


Fig. 5. The limited-selective action of radiation in the collisional excitation of high vibrational levels.

where Z_{rot} is the average number of collisions necessary for the rotational relaxation and τ_{coll} is the average time between gas-kinetic collisions. This value is of the same order of magnitude or even more than the vibrational-translational relaxation time, $\tau_{\text{vt}} = \tau_{\text{coll}} Z_{\text{vt}}$. Therefore, translational heating will compete with vibrational heating, and the nonselective thermal excitation will prevent selective-limited reactions.

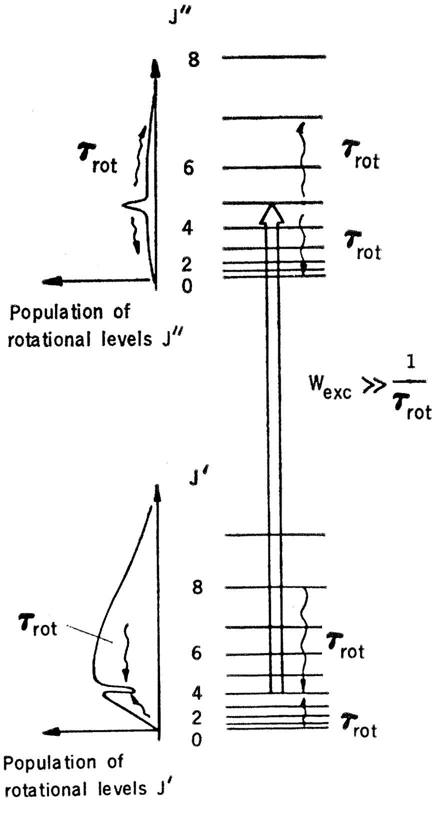


Fig. 6. The "narrow throat" effect in the excitation of molecular vibrations with monochromatic laser radiation.

Chemical Reactions of Excited Molecules

Now let us consider various schemes of selective reactions. As mentioned above, one possibility is a fast chemical reaction with selectively excited molecules, which requires a small number of collisions between molecules.

Selective reactions with atoms and molecules in excited electronic states were investigated in several experiments carried out with both the usual sources of monochromatic radiation (*2–9*) and lasers (*12*). As a rule the selectivity coefficient S did not exceed a few percent, except for the photochemical separation of ortho and para I_2 (*3*) and of the isotopes ^{12}C and ^{13}C (*9*). The quantum yield of the selective photocatalysis, η, defined as the average number of A molecules selectively reacted per quantum of radiation absorbed,

$$\eta = \frac{\text{number of A molecules in reaction}}{\text{number of absorbed quanta}}$$

is usually rather small.

The main difficulty was that chemical reactions of molecules occur after a relatively large number of collisions, over 10^2 (*18*). This number of collisions leads to the loss of excitation selectivity. A low quantum yield is also due to the short lifetime of electronic states relative to radiation decay. Excitation of atoms and molecules in metastable states can be used, as with Hg (*6*), but with it one can study only a limited group of reactions.

The selective catalysis of chemical reactions with infrared radiation became possible only with the use of powerful molecular lasers. Obtaining high selectivity and high quantum yields is also problematic with this method because many collisions are necessary for the vibrationally excited molecule to react. The best result was obtained by Mayer *et al.* (*19*), with a mixture of methanol and completely deuterated methanol irradiated by a 2.7-μm hydrogen fluoride laser; the vibrationally excited CH_3OH molecules selectively reacted. A high selectivity, $S \gg 1$, was obtained in this experiment, at a low quantum yield. The high selectivity may have been due to the considerable difference in chemical properties and vibrational frequencies between CH_3OH and CD_3OD.

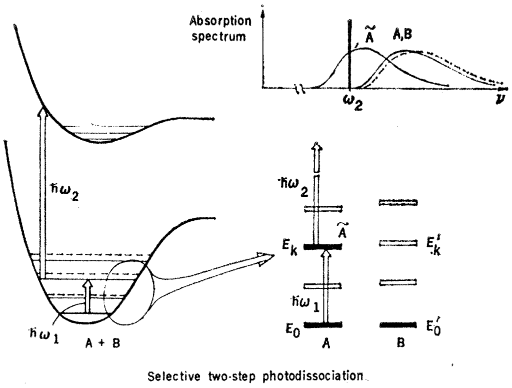
The chemical method of bonding selectively excited atoms and molecules probably has some potential, but it is difficult to find effective fast chemical reactions in every case.

Dissociation of Excited Molecules

From our point of view, the methods based on the fast ionization or dissociation of selectively excited atoms or molecules are useful for conserving the selectivity and for obtaining a high quantum yield (*20*). In this case the final product ions, atoms, or radicals are stable enough, and it is possible, without risk of fast relaxation or excitation transfer, to realize the next stage, the collection of ions or the chemical bonding of atoms and radicals (*21*).

We can use two types of dissociation processes: (i) photodissociation of selectively excited molecules by additional laser radiation (*20, 22*), whose intensity can be made rather high so that the photodissociation rate is more than the rates of relaxation and excitation transfer, and (ii) predissociation of selectively excited molecules (*23*) due to the intersection of molecular electronic terms.

The two-step selective photodissociation of molecules is carried out with radiation at two different frequencies, ω_1 and ω_2 (Fig. 7). The $\hbar\omega_1$ photon excites, say, a definite discrete spectrum of vibrational energies of the A molecules. The radiation at ω_2 transfers vibrationally excited A molecules ($\tilde{A}$) into the excited electronic state from which dissociation occurs. The transfer into the excited state takes place before vibrational relaxation and before the transfer of excitation to the B molecules. To photodissociate only $\tilde{A}$ molecules, the energy $\hbar\omega_2$ is chosen somewhat lower than the photodissociation limit of nonexcited A and B molecules, but higher than the red boundary of photodissociation of the excited molecules. As a result of the selective two-step photodissociation, radicals and atoms of particular molecules are created in the gas mixture, and these can enter into chemical reactions with the acceptor molecules R present in the mixture. The selectivity of this process is extremely high, since in fact it is limited by the Doppler width of the molecular rotational-vibrational transitions (*24*). Two-step selective photodissociation can be carried out by using as an intermediate state not only vibrational levels, but discrete electronic-vibrational levels.



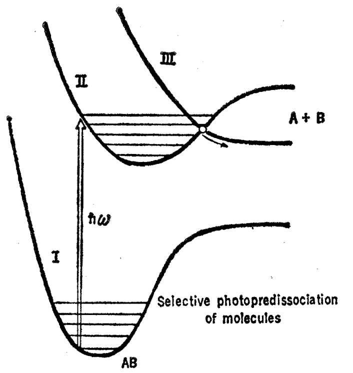


Fig. 7 (left). Schema of the process of molecular two-step selective photodissociation. Fig. 8 (right). Schema of the molecular photopredissociation process.

With the excitation of the molecular electronic states, in some cases, we can obtain selective breaking of a bond in a one-step process. This is due to the photopredissociation process in a molecule with intersecting electronic terms (Fig. 8). A molecule oscillating in the potential well of the excited stable electronic state II can, at the appropriate point, pass into the unstable level III, which leads to dissociation. This process is called predissociation (*25*). The predissociation probability of the selectively excited molecule can be 10^7 to 10^{10} sec^{-1}, that is, higher than the probabilities of relaxation and excitation transfer:

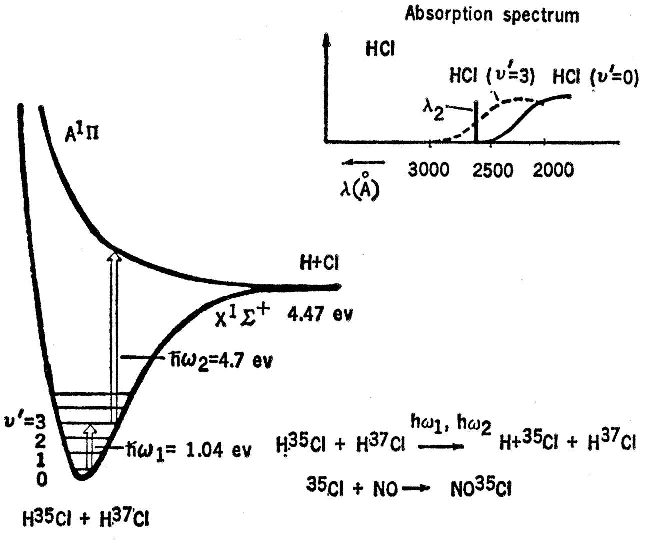
$$P_{\mathrm{pre}} \gg Q_{\mathrm{A^*B}}, \frac{1}{\tau_{\mathrm{rel}}} \qquad (5)$$

According to the uncertainty principle, the predissociation decay of the excited state widens the narrow spectral absorption line up to $\Delta\omega = P_{\mathrm{pre}}$. However, if the predissociation does not occur too fast, say $P_{\mathrm{pre}} < 10^{10}$ sec^{-1}, then it broadens this line by a rather small amount, about $\Delta\nu/\nu = 10^{-5}$ to 10^{-6}, which is much less than the isotopic frequency shift. Therefore, the excitation process involving a predissociation state can have a high selectivity.

Selective Two-Step Photodissociation of HCl

The laser device used for the photodissociation of HCl is described in (*20*). It involves the powerful pulsed laser of neodymium glass, having a narrow frequency-tuned radiation line. This tuning is carried out with a diffraction-grating dispersive cavity within the amplification band of neodymium glass, 200 Å wide at the 10,600-Å wavelength, the generated line width being less than 0.02 Å. Then the laser pulse of 20 nsec is directed into two parallel channels, transforming its radiation frequency. In the infrared channel the pulse frequency is shifted by stimulated Raman scattering (SRS) in a molecular liquid so that it falls into coincidence with the molecular absorption line. To excite the third vibrational level of HCl there should be radiation in the 1.18-μm region. The appropriate shift in the laser frequency of 1100 Å is obtained by SRS in pyridine. More precise frequency tuning is made with a diffraction grating (up to 1 Å) and the Fabry-Perot etalon inside the cavity (up to 0.1 Å). A precise measurement of the wavelength of the infrared radiation is difficult to realize in one pulse. Therefore, the infrared channel frequency was doubled in the nonlinear crystal potassium dihydrogen phosphate (KDP), and then it entered a spectrograph with a photographic registration. In the ultraviolet channel the powerful pulse frequency was doubled twice in KDP crystals and the radiation pulse at 2650 Å, together with the infrared channel pulse, was directed into the cell containing HCl.

The lower energy states of HCl and the ultraviolet absorption spectrum are depicted in Fig. 9. The infrared channel radiation excites some of the HCl molecules to the third vibrational level, so that the molecules have an excess energy of 1.04 electron volts. It is possible to transfer the HCl from the ground electronic state $X\,^1\Sigma^+$ by radiation in the 2000-Å region into the unstable electronic state $A\,^1\Pi$; that is, the ultraviolet radiation results in breaking the bond of the molecule. An energy of about 6 ev is necessary for this. However, for excited molecules the energy required to break the bond should be smaller by about the excitation energy. It corresponds to a shift in the ultraviolet absorption line by about 500 Å. The wavelength of the ultraviolet channel radiation was chosen so that it did not lie within the usual absorption spectrum of nonexcited HCl molecules (that is, did not photodissociate nonexcited molecules), but coincided with the absorption band of excited mole-



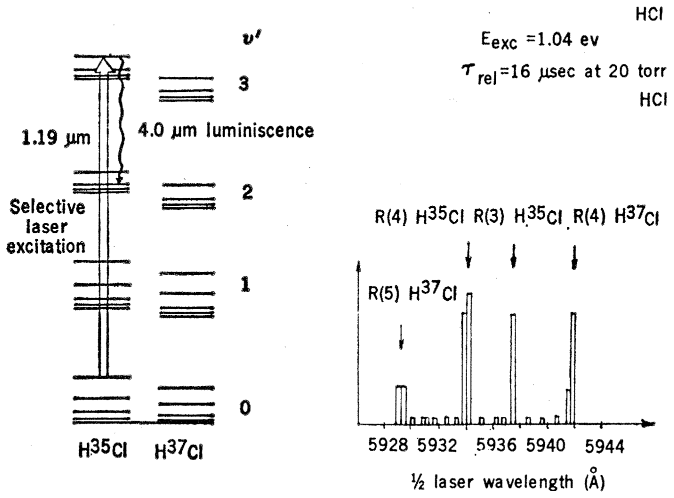


Fig. 9 (left). Two-step selective photodissociation of HCl. Fig. 10 (right). Lower rotational-vibrational levels of HCl and the dependence of the infrared luminescence intensity in the 4-µm region on the infrared excitation wavelength.

cules, as shown at the top in Fig. 9.

By tuning the infrared channel radiation on the absorption line of $H^{35}Cl$ or $H^{37}Cl$ one can obtain selective photodissociation of HCl with the chosen Cl isotope. The nitric oxide molecule can be used as an acceptor for Cl atoms, and it is added to the cell with HCl. The selectivity of the excitation for HCl molecules with the chosen Cl isotope was controlled in the following way. The lower rotational-vibrational levels of $H^{35}Cl$ and $H^{37}Cl$ are illustrated in Fig. 10. By tuning the infrared wavelength we can tune in to one out of several absorption lines. The excited HCl molecules can emit in cascade transitions between the vibrational levels radiation at 3.6 to 4.0 µm. Figure 10 shows (*26*) the dependence of the infrared luminescence intensity in the region of 4.0 µm on the wavelength of the infrared channel radiation, that is, the wavelength of its second harmonic. The observed intensity maxima coincide exactly with the absorption lines of $H^{35}Cl$ and $H^{37}Cl$. The relaxation time of vibrationally excited HCl molecules, τ_{rel} ($v'' = 3$), is 16 µsec at an HCl pressure of 20 torr, determined with the infrared luminescence decay time.

Selective Two-Step Photodissociation of NH_3

Figure 11 shows schematically the potential curves for one normal oscillation ν_2 and also the lower vibrational levels of the ground state $X\ {}^1A_1$ of NH_3 (*25, 27*). The movements of atoms for the oscillations considered is shown at the top. The potential curve for the ground electronic state is symmetrical and has a potential barrier that makes it possible for the nitrogen atom to tunnel through the plane of the hydrogen atoms. It results in the so-called inversion splitting of each energy level. This splitting is very small for the lower vibrational level, and is in the radio frequency region. The inversion splitting increases for excited vibrational levels. In the excited electronic state the molecule becomes flat, and therefore the potential curve has its minimum at the zero amplitude of oscillations.

The experiment was carried out in the following way. The pulsed CO_2 laser radiation at 10.6 µm excited the first vibrational level of ${}^{14}NH_3$ or ${}^{15}NH_3$. From the ground vibrational state the molecule can be excited by radiation into the various vibrational levels of the excited electronic state. This corresponds to the existence of several lines in the NH_3 ultraviolet absorption spectrum with the evident vibrational structure (*25*). For NH_3 molecules excited with a CO_2 laser the absorption spectrum is shifted into the red region. It is essential that a new line appears in the ultraviolet absorption spectrum corresponding to the transitions from the first excited vibrational level of the lower electronic state to the zero vibrational level of the excited electronic state; this is depicted in Fig. 11. The kinetics of the appearance and disappearance of this line gives much information concerning relaxation processes in NH_3 and mixtures of ${}^{14}NH_3$ and ${}^{15}NH_3$.

The most important property of electronically excited NH_3 molecules is their instability in spite of the stable character of the potential curve. The fact is that for other normal oscillations the corresponding potential curves are of a decay character, and the excited molecule can transfer into them (*25*). As a result, about 15 percent of the NH_3 molecules decay into H atoms and NH_2 radicals when they are selectively excited. So, in the experiments reported in (*28*) the selective two-step photodissociation of NH_3 was carried out. By diluting the isotopic mixture of ${}^{14}NH_3$ and ${}^{15}NH_3$ with helium it was possible to prevent excitation resonance exchange between the molecules and to ensure selectivity of the bond breaking in NH_3 with the chosen nitrogen isotope. By this method, laser separation of the nitrogen isotopes was achieved for the first time (*13*), with the selectivity coefficient (degree of enrichment) $S \gg 1$ (from a few units up to hundreds under the different conditions of the experiment).

Optimal Conditions of Two-Step Photodissociation

The method of two-step selective photodissociation enables us to dissociate molecules of a definite type in a gas mixture, that is, to obtain definite radicals instead of the "muddle" of radicals created in the usual flash photolysis of a gas mixture. Therefore, two-step photodissociation, in principle, is a universal method for controlled selective chemical reactions. Let us now consider some conditions for optimal use of the two-step photodissociation process.

To have the dissociation of selectively excited molecules prevail over that of nonselectively (thermally) excited molecules, the $\hbar\omega_1$ quantum of energy should satisfy the condition

$$\hbar\omega_1 \gg kT \qquad (6)$$

To have the photodissociation rate of selectively excited molecules considerably exceed that of nonexcited molecules with the same radiation, the width of the red wing of the continuum absorption spectrum corresponding to the photodissociation, $\Delta\omega_{\text{wing}}$, must satisfy the condition

$$\hbar\omega_1 \gg \Delta\omega_{\text{wing}} \qquad (7)$$

To fulfill conditions 6 and 7 it is advisable to excite high vibrational levels all at once [this can be done by pumping overtones and compound molecular frequencies (*26*) or by the successive excitation of a high vibrational level with a set of several frequencies], or to excite molecular electronic states.

For the photodissociation of all the excited molecules it is necessary that the photodissociation rate S_{pd} should be of the same order or more than the excitation rate W_{exc}. The case $W_{\text{exc}} \simeq S_{\text{pd}}$ is preferable. Since the absorption coefficients at the frequencies ω_1 and ω_2 are considerably different, for a complete use of the radiation one should make the radiation path through the molecules as long as possible (optically dense cell). Is this compatible with the photodissociation of most of the excited molecules? A detailed analysis (*29*) shows that molecular two-step photodissociation at a large optical depth satisfies simultaneously the following important requirements:

1) Production of a large relative yield of the two-step photodissociation products (dissociation of 50 percent of the molecules absorbing ω_1 radiation).

2) Selective breaking of bonds of the molecules in a large volume.

3) Full use of the radiation.

4) Achievement of the maximum quantum yield, approximately 0.5.

To control chemical reactions with selective two-step photodissociation (or one-step photopredissociation) it is important to have an effective chemical reaction for "binding" the free atoms and radicals. A high concentration of "hot" radicals with an excess of energy can lead to secondary processes violating the reaction selectivity. With a relatively small concentration of radicals, sufficient dilution of the mixture with a buffer gas and the choice of an effective acceptor can prevent selectivity loss induced by secondary processes.

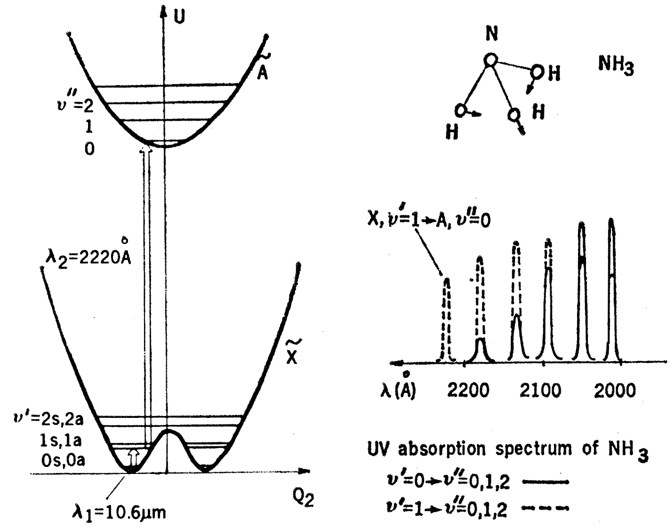


Fig. 11. Two-step selective excitation of NH_3 into the state from which predissociation occurs. The atomic motions for the oscillations involved are shown at the upper right. *U* is the potential energy of the molecule.

Optical Separation of Isomeric Nuclei

The selectivity of chemical reaction control can be so high that we can think about the optical separation of isomeric nuclei (*30*), that is, nuclei different not in their isotopic composition, but only in their excitation energy. In fact, according to Einstein's equivalence principle, excitation of the nucleus should increase the mass by the value

$$\Delta m = E_{\text{exc}}\, c^{-2}$$

where *c* is the speed of light. At an excitation energy, E_{exc}, of 0.5 million electron volts, Δm is equal to the mass of the electron. The growth in weight of the excited nucleus by Δm should result in a decrease of the molecule's infrared vibrational frequency. The isomeric shift value is small, but quite observable with laser spectroscopy. The difference in the absorption spectra of molecules with excited and unexcited nuclei permits fast separation of the isomeric nucleus by two-step photoionization of atoms and photodissociation of molecules. This method may be used for preparation of the active medium for a practicable x-ray nuclear laser (*31*).

Summing up, we can say that laser radiation, together with special schemes for its action on substances, enables us to control to a high degree selective reactions with atoms and molecules having the same electronic structure, but differing in nuclear composition (isotope separation), nuclear spin orientation (separation of "ortho" and "para" molecules), or nuclear excitation (separation of isomers). In the near future we can expect considerable progress in this area.

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32. I am grateful to Dr. R. V. Ambartzumian for many helpful discussions of the questions considered in this article.

Chemical Structures of Pancreatic Ribonuclease and Deoxyribonuclease

Stanford Moore and William H. Stein

In introducing this summary of experiments on two enzymes, we wish to indicate that the information is representative of what biochemists are obtaining about many proteins. An understanding of the host of reactions in which proteins participate in living cells requires information on the molecular architectures of a wide variety of proteins of different origins and different functions. Such information is coming from laboratories all over the world and draws upon a rich heritage of experience from many investigators. And such knowledge is fundamental to progress in medical research; the Nobel awards this year in chemistry (concerning ribonuclease) and in physiology or medicine (concerning antibodies) both concern basic researches on the chemistry and the biology of proteins.

Occasionally (*1*) it has been educational to write the structural formula for ribonuclease in full, in terms of its 1876 atoms of C, H, N, O, and S. Portrayal of the complete molecule with all of the atoms of the amino groups, carboxyl groups, hydroxyl groups, guanido groups, imidazole rings, phenolic groups, indole rings, aromatic, aliphatic, and thioether side chains, sulfhydryl groups, and disulfide bonds, helps in the visualization of the almost infinite number of ways in which such groups could be arranged. This characteristic of proteins makes it possible for nature to design catalysts for such a variety of specific reactions. There is no law that says that a nucleic acid or a polysaccharide could not be an enzyme. But it is understandable that the enzymes so far isolated have turned out to be proteins; a protein is equipped to participate, sometimes through cooperation with coenzymes, in the whole lexicon of organic reactions that require catalysis in the living cell.

Purification of Ribonuclease

The first step in the study of the structure of ribonuclease was, of course, its purification. Ribonuclease was first described in 1920 by Jones (*2*), who showed that there was present in beef pancreas a relatively heat-stable enzyme capable of digesting yeast nucleic acid. Dubos and Thompson (*3*) partially purified the enzyme some 18 years later, and in 1940 Kunitz (*4*) described the isolation of bovine ribonuclease in crystalline form after fractionation by ammonium sulfate precipitation. In order to be as certain as possible that we were beginning the structural study with a single molecular species, we undertook to apply the potential resolving power of ion exchange chromatography to ribonuclease (Fig. 1). While Werner Hirs, in our laboratory, was exploring the chromatographic purification of ribonuclease on the polymethacrylic resin Amberlite IRC-50 (*5, 6*), Paléus and Neilands (*7*), in Stockholm, were studying cytochrome c on the same exchanger. These two proteins were the first molecules of their size to be thus purified. The best resolution for ribonuclease (Fig. 2) is now obtained (*8*) with an exchanger invented in Uppsala, a sulfoethyl cross-linked dextran, which was a development that grew from Porath and Flodin's (*9*) experiments on gel filtration and drew upon Sober and Peterson's (*10*) emphasis on the advantages of a carbohydrate matrix for the exchanger.

When pancreatic extracts were analyzed without prior fractionation, two peaks of enzymatic activity were observed by us (*6*) by ion exchange chromatography and by Martin and Porter (*11*) by partition chromatography. The major component, ribonuclease A, was selected for the first structural studies. [In later independent experiments, Plummer and Hirs (*12*) isolated ribonuclease B in pure form from pancreatic juice and showed it to be the same as A but with the addition of a carbohydrate side chain attached to one asparagine residue.]

Amino Acid Analysis

The second step in the structural study of ribonuclease A was the determination of the empirical formula of the chromatographically homogeneous protein in terms of the constituent amino acids. Our appreciation of the importance of quantitative amino acid analysis began in the late 1930's when we had the special privilege of starting our postdoctoral studies in apprenticeship to Max Bergmann (*13*). In 1945 it was possible to take a new look

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The authors are professors of biochemistry at the Rockefeller University, New York 10021. This article is a combined text of the lecture delivered by Dr. Moore and the lecture delivered by Dr. Stein in Stockholm, Sweden, on 11 December when they received the Nobel Prize in Chemistry, a prize they shared with C. B. Anfinsen. The article is published here with the permission of the Nobel Foundation and will also be included in the complete volume of *Les Prix Nobel en 1972* as well as in the series Nobel Lectures (in English) published by the Elsevier Publishing Company, Amsterdam and New York. Dr. Anfinsen's lecture will be published in a subsequent issue of *Science*.